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Photospheric and chromospheric activity on EY Dra *

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Magnetic activity in the photosphere and chromosphere of the M dwarf EY Dra is studied and possible correlations between the two are investigated using photometric observations in the V and R bands and optical and near infrared spectroscopy. The longitudinal spot configuration in the photosphere is obtained from the V band photometry, and the chromospheric structures are investigated using variations in the Hα line profile and observations of the Paschen β line. The shape of the V band light-curve indicates two active regions on the stellar surface, about 0.4 in phase apart. The spectroscopic observations show enhanced Hα emission observed close to the phases of the photometrically detected starspots. This could indicate chromospheric plages associated with the photospheric starspots. Some indications of prominence structures are also seen. The chromospheric pressure is limited to $\log \mathrm{m_{TR}} < -4$ based on the non-detection of emission in the Paschen β wavelength region.

1 Introduction

EY Dra (RE 1816+541) is a very active M dwarf that was discovered by the ROSAT extreme ultraviolet (EUV) all sky survey in the early 1990's (Pounds et al. 1993). The optical counterpart of the EUV source RE 1816+541 was first observed by Jeffries et al. (1994) who did a thorough analysis of the object using optical spectroscopy. They observed strong, variable Hα emission and molecular lines, and concluded that the source is an M1-2e dwarf, and thereby one of the most active stars in the solar neighbourhood. They also discovered that EY Dra is a very rapid rotator with a $v \sin i \approx 61\,\mathrm{km\,s^{-1}}$ and a rotation period of about 12 $\sin i$ hours. Jeffries et al. (1994) determined the radial velocity of the target to be $-21.9 \pm 1.5\,\mathrm{km\,s^{-1}}$. A higher spectral and temporal resolution study of EY Dra was carried out by Eibe (1998) who found significant variations in the Hα profile, which were interpreted as chromospheric plages and prominence clouds higher up in the atmosphere, but still below the corotation radius.

The first photometric observations of EY Dra were obtained by Schwartz et al. (1995) who established the star's brightness to be 11.83 in the V band and the colours of (B-V)=1.45, (V-R)=0.96 and (R-I)=1.05, also indicating a cool star. The first long-term photometric study of EY Dra was carried out by Robb & Cardinal (1995) who measured the rotation period of $0\overset{\mathrm{d}}{.}4589$ and remarked that the light-curve shape indicated two large spots or active regions on the stellar surface. Barnes & Collier Cameron (2001) used Doppler imaging techniques to obtain the first precise surface structure maps of EY Dra. These surface temperature maps showed spots on a very large latitude range ($20^\circ - 80^\circ$), but no polar spot.

In this paper we carry out the first simultaneous photometric and spectroscopic observations of EY Dra to study the photospheric spots and correlate them with the variability seen in the chromosphere. The longitudinal spot configuration is obtained from the photometric observations and the chromosphere is studied with the high resolution Hα line observations. In addition, medium resolution near infrared (NIR) observations of the Paschen β line were used to further investigate the chromosphere of EY Dra.

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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2 Observations

All the observations presented in this paper were obtained at the Nordic Optical Telescope in early July 2006. The optical data were taken using ALFOSC, which is owned by the Instituto de Astrofisica de Andalucia (IAA) and operated at the Nordic Optical Telescope under agreement between IAA and the NBIfAFG of the Astronomical Observatory of Copenhagen. The NIR spectroscopy was obtained using NOTCam.

All the observations have been phased using the ephemeris, HJD $= 2449927.752 + 0\overset{\mathrm{d}}{.}4589 \times$ E, from Robb & Cardinal (1995).

2.1 Photometry

Photometric observations of EY Dra in the V and R bands were obtained with ALFOSC. The detector is an E2V Technologies 2k back-illuminated CCD with 13.5μ pixels, giving a field-of-view (FOV) of $6.5' \times 6.5'$. This FOV made it possible to observe the comparison star (GSC 0390400259) and the check star (GSC 0390400361) in one frame together with the target, and thus do differential photometry of EY Dra. The comparison star and the check star are both from the Hubble Space Telescope Guide Star Catalogue (Jenkner et al. 1990).

The photometric observations of EY Dra were obtained during the nights starting 2006 July 1 and July 3. The exposure time was 1–3 seconds in the V band and 1 second in the R band. In total observations from 9 rotational phases were obtained. Each observation consisted of 1-7 individual exposures that were first bias and sky flat field corrected, and then averaged after the determination of the differential magnitude (object-comparison star). The error of each phase was determined as the standard deviation of all the points used in the average and divided by the square-root of the number of observations. The data reduction was done and the photometry obtained using Image Reduction and Analysis Facility (IRAF) distributed by KPNO/NOAO. Table 1 gives more details on the photometric observations.

Table 1 Details of the photometric observations of EY Dra. The Heliocentric Julian Date, rotational phase, instrumental differential magnitude, the error of the magnitude and the number of observations used to obtain the magnitude are given for both the V and R bands. The error for each data point is the standard deviation of the measurements divided by the square root of the number of the measurements.

HJD 2453000+	phase	mag	error	no
V band				
918.41440	0.148	-1.197	0.002	4
918.46784	0.265	-1.202	0.010*	1
918.52188	0.382	-1.184	0.004	3
918.61168	0.578	-1.163	0.003	3
920.41944	0.517	-1.173	0.004	5
920.53116	0.761	-1.172	0.003	2
920.58829	0.885	-1.163	0.004	3
920.62317	0.961	-1.149	0.007	2
920.67216	0.068	-1.178	0.003	3
R band				
918.41845	0.157	-1.772	0.003	4
918.46948	0.268	-1.773	0.003	3
918.52399	0.387	-1.757	0.004	3
918.61382	0.583	-1.738	0.003	3
920.42230	0.524	-1.749	0.004	3
920.54907	0.800	-1.718	0.010*	1
920.59153	0.892	-1.732	0.002	7
920.62466	0.965	-1.729	0.004	3
920.67405	0.072	-1.749	0.002	3

*) Only one observation was obtained during this phase, so no standard deviation of the measurements could be obtained to estimate the error of the data point. An error value of 0.010 was adopted.

2.2 Optical spectroscopy

Optical spectroscopy of EY Dra around the Hα line was obtained using ALFOSC, grism#17, and a $0\overset{''}{.}5$ off-set slit during the nights starting 2006 July 1 and July 3. This instrument configuration gives a resolving power ($\lambda/\Delta\lambda$) of 10 000 and a spectral coverage approximately from 6200 Å to 6700 Å. Due to the fringing in the E2V CCD starting around 6400 Å, the observations were done in sets of five 120 second exposures. Between each separate spectrum the object was moved along the slit to be able to remove this fringe pattern from the observations. After every five object exposures, two Halogen flat fields and one Neon arc spectrum were obtained. After basic reduction steps (bias subtraction, image trimming and flat field correction) the five consecutive observations were combined to obtain 15 better signal-to-noise (S/N) spectra with minimum fringe patterns. A radial velocity standard (HD 103095) and a B star (BD+33 2642) were also observed. The B star spectrum was used for checking contribution from terrestrial lines in this spectral region. The reductions were carried out using the 4A reduction package (Ilyin 2000). More details on the observations are given in Table 2.

2.3 Near IR spectroscopy

The medium resolution NIR observations were obtained in the region around the Paschen β line, using the NOTCam with the high resolution camera, grism#1, and J filter. This instrument configuration gives a resolving power ($\lambda/\Delta\lambda$) of 5700 and a wavelength coverage of 12620–13520 Å. The detector is a Rockwell Science Center "HAWAII" array with $1024 \times 1024 \times 18.5\,\mu$m pixels in HgCdTe. Two spectra with 4×450 sec exposure time were obtained in the evening of 2006 July 5.

For removing the IR background we used an ABBA dithering pattern along the slit, which gave 4 separate spec-

Table 2 Optical spectroscopy of EY Dra. Heliocentric Julian Date, rotational phase, radial velocity obtained with IRAF fxcor task and the S/N per pixel are given.

HJD 2453000+	phase	RV [$\mathrm{km\,s^{-1}}$]	S/N
918.44256	0.210	-21.6 ± 2.7	150
918.45631	0.239	-21.3 ± 3.0	162
918.48694	0.306	-17.7 ± 3.6	128
918.49864	0.332	-17.6 ± 3.3	94
918.50970	0.356	-15.6 ± 3.1	93
918.62720	0.612	-28.7 ± 3.3	58
920.39421	0.462	-25.3 ± 2.5	116
920.56335	0.831	-22.7 ± 2.1	139
920.57345	0.853	-15.9 ± 2.3	164
920.64873	0.017	-13.4 ± 2.3	133
920.66079	0.043	-13.5 ± 2.2	114
920.69449	0.117	-31.8 ± 2.6	131
920.70800	0.146	-33.3 ± 2.3	108
920.71966	0.172	-31.9 ± 2.5	124
920.72899	0.192	-33.7 ± 2.0	91

tra that were combined into one spectrum during the reductions. Each spectrum was obtained using non-destructive readouts which were acted upon by a linear regression calculation reducing the Poisson noise of the observation. The whole spectral region shows strong fringing pattern that did not completely disappear even after the flat fielding. For removing the skylines an A0 star (HD 172728) was observed as an atmospheric standard. The data were reduced using IRAF.

3 Radial velocity

The radial velocity of EY Dra was investigated from the lines in the wavelength region 6400–6500 Å using the IRAF fxcor routine. Before the cross-correlation all three radial velocity standard observations were combined to one higher S/N spectrum, after which the resulting spectrum was spun-up to the $v \sin i$ of EY Dra, 61 $\mathrm{km\,s^{-1}}$ (Jeffries et al. 1994). The measurements for the individual phases are given in Table 2.

The radial velocity for the whole dataset is -22.6 ± 1.9 $\mathrm{km\,s^{-1}}$. This is in agreement with the values published by (Jeffries et al. 1994) and Eibe (1998). The radial velocities obtained from each night's data set are -20.1 ± 1.9 $\mathrm{km\,s^{-1}}$ and -24.3 ± 2.9 $\mathrm{km\,s^{-1}}$, for 2006 July 1 and July 3, respectively. Note that the errors stated assume that the errors are random.

4 Photosphere

The V and R band light-curves of EY Dra together with the errors of the individual points are shown in Fig. 1. The V band light-curve has in general a W shape. The phases 0.76 and 0.88 form the bump seen in the broad light-curve minimum. The two minima in the V band light-curve are located around the phases 0.3–0.75 and 0.85–1.15. The main maximum occurs around the phases 0.15–0.3. On the whole, the V band light-curve indicates two active regions separated by about 0.4 in phase on the surface of EY Dra.

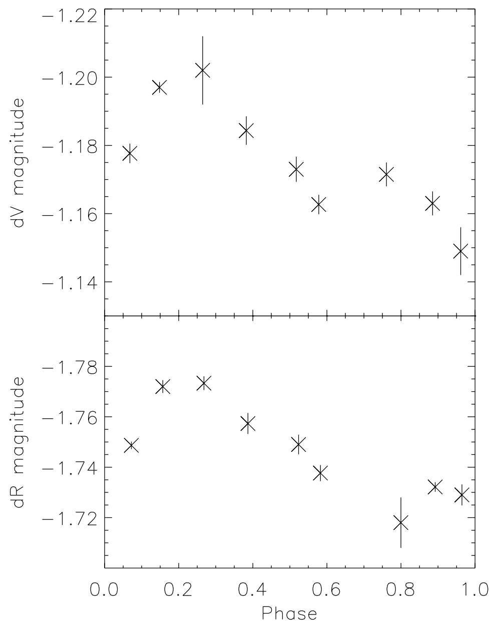

Fig. 1 Differential V and R band photometry of EY Dra with the errors.

In the V band observations of Robb & Cardinal (1995) from 1995 similar W shape was present. Also, the photometry obtained before and after our observations at the Konkoly observatory (Vida & Oláh 2006) exhibits the W shape. This photometry, which will be published later, is shown in Fig. 2 together with our observations. In the plot the plus-signs are data obtained at the Konkoly observatory between 2006 April 21 and May 12, crosses are the NOT observations and the stars are observations from the Konkoly observatory obtained between 2006 July 22 and August 8. The relatively large scatter seen in the latter Konkoly observations is most likely due to the non-optimal observing conditions during this time period.

In the R band observations obtained at NOT the W shape is not really seen. The light-curve shows a broad minimum around the phases 0.8–1.1. The observations at the phase 0.89 show indications of the bump, but unfortunately the phase 0.8, which also would be in the bump, only has one individual observation and as such a large photometric error. The R band observations from the Konkoly observatory show the W shape for the time periods before and after the NOT observations. When the instrumental (V-R) colour is calculated, no clear modulation of the colour with the stellar rotation period is seen. But the data point at the phase 0.8 deviates strongly from the others.

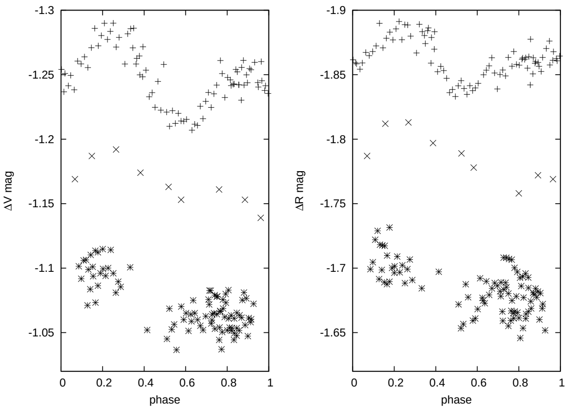

Fig. 2 Differential V (left) and R (right) band observations of EY Dra. The plus-signs are data obtained at the Konkoly observatory on average 62 days before the NOT observations, crosses are the NOT observations and the stars are observations obtained at the Konkoly observatory on average 27 days after the NOT observations. Offsets have been applied to the individual datasets to show the light-curve shapes better.

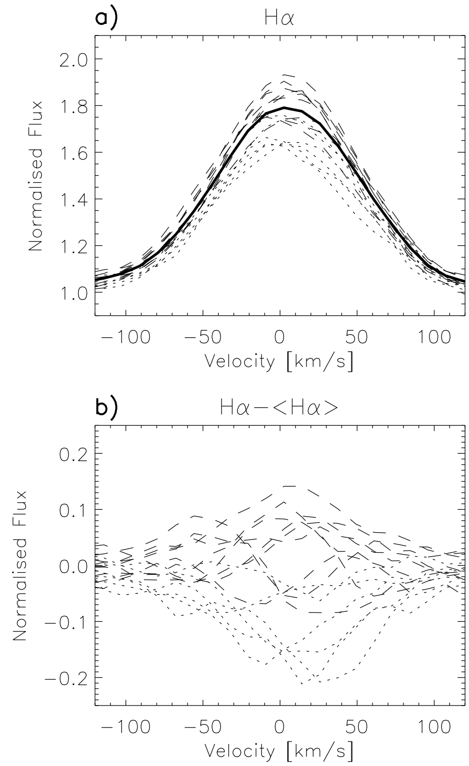

Fig. 3 The Hα line variations in EY Dra. a) All the 15 individual Hα observations obtained in this study. The line profiles are plotted against the velocity obtained in relation to the rest wavelength of the Hα. The radial velocity has been removed from all the profiles. The thick line gives the average line profile. b) The residual variations in the Hα. The mean profile has been subtracted from all the observations. In both of the plots the dotted line gives the observations from the night starting 2006 July 1 and the dashed line observations from the night starting 2006 July 3.

5 Chromosphere

5.1 Hα line

In EY Dra the Hα line is a quite broad emission feature. All the profiles from the 15 epochs observed in this study are plotted in Fig. 3**a**. The radial velocities stated in Table 2 have been removed from the profiles. As can be seen, the strength of the profile varies significantly with time. The thick line in the plot is the mean of all the profiles. The residual variations in the profile after the mean profile has been subtracted are given in Fig. 3**b**. For both plots in Fig. 3 the data from the night starting 2006 July 1 are presented with dotted lines and the data from the night starting 2006 July 3 are given by dashed lines.

To study the Hα behaviour in more detail the profiles showing the difference between the observations and the mean spectrum were investigated more thoroughly. In Fig. 4 a dynamic spectrum constructed from these difference profiles is shown. Brighter colours in the plot correspond to enhanced emission and the darker colours to the emission that is less than the average. The phases of the observations are shown with crosses on the plot. The data for the phases where there are no observations are just interpolations between the closest phases with data.

The relatively low spectral resolution of the data does not allow such a detailed analysis of the chromospheric absorption and emission clouds as was done in Eibe (1998). However, our data also indicates chromospheric structures. The dynamic spectrum clearly shows enhanced emission in the Hα around the phases 0.75–1.1, and a small enhancement around the phase 1.5. In the dynamic spectrum the features with increased and decreased Hα emission often seem to move from blue to red, and could indicate chromospheric plages and prominences. Especially the enhanced emission around the phases 0.75–1.1 seems to move from blue to red, and could be associated with a plage. The other enhancement, around the phase 0.5, is, due to the sparse data sampling, only seen in one spectrum. The feature could be associated with a plage, though this cannot be confirmed. The feature of decreased Hα emission around the phases 1.25–1.5 is seen to move across the line profile, and could thus be associated with a prominence cloud. It has to be noted though, that the interpolation used to fill the phase gaps in the dynamic spectrum can artificially enhance the perception of moving features.

5.2 Paschen β line

Atmospheric models of M dwarfs calculated by Short & Doyle (1998) show that the Paschen β line profile can be used to determine the chromospheric pressure and thereby the activity level in such stars. This spectral line, which is in

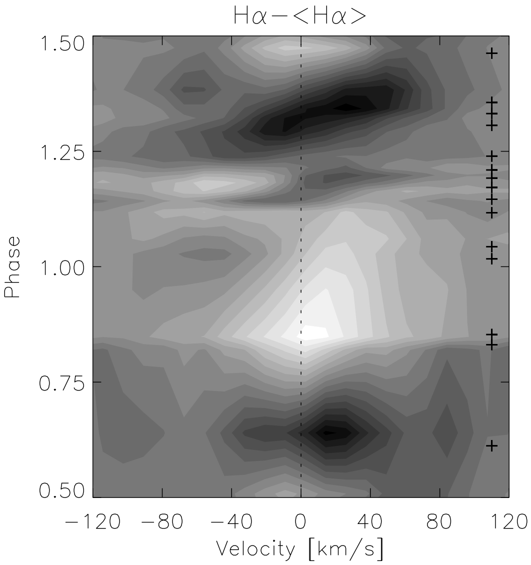

Fig. 4 Dynamic spectrum of the Hα line of EY Dra. The image shows the difference profiles after the mean profile has been subtracted from the observations. Bright colour means more emission in the Hα. The measured radial velocity for each observations has been removed from the profiles. The crosses on the right hand side of the plot give the phases of the observations and the dashed line the 0 velocity.

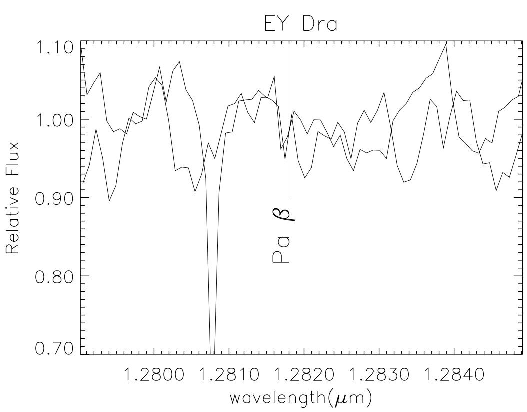

Fig. 5 The final two background subtracted, flat fielded, normalised and radial velocity corrected NIR spectra of EY Dra. The absorption line present in one spectrum and not in the other is a telluric feature. The vertical line is the position where the Paschen β line centre should be if present in the spectra.

the NIR part of the spectrum (λ=12 818 Å), was therefore also observed.

Fig. 5 shows the two observed NIR spectra of EY Dra around the Paschen β line. The resolution of the spectra is poor and a strong fringing pattern is seen in the spectra even after the flat field correction. Still, it is clear from the observations that no strong emission line is seen around the Paschen β wavelength.

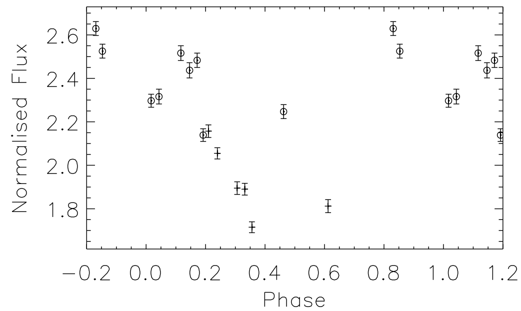

Fig. 6 The variation of the Hα flux obtained by integrating over the whole line and plotted against the rotational phase. The observations from the night starting 2006 July 1 are given by crosses and the observations from the night starting July 3 by circles.

6 Discussion

6.1 Night to night variation of the Hα

When looking at Fig. 3 it seems that in general the observations obtained during the night starting 2006 July 1 (dotted line) show less emission than the ones observed during the night starting 2006 July 3 (dashed line). This could be caused by a real difference in the activity level between the two nights, or by the observations from the first night coinciding with the less active rotational phases. In Fig. 6 the integrated Hα flux is plotted against the phase. The behaviour seen during the second observing night (circles), can be interpreted as more or less constant Hα emission, whereas the behaviour during the first observing night (crosses), shows clearly diminishing activity with increasing phase.

In principal the behaviour seen during the first observing night could be explained by a gradual decline of a chromospheric flare. On the other hand, if the behaviour seen during the first observing night is due to a declining flare, then flux seen in the phases 0.3–0.35 indicates the normal Hα flux. This would imply that the observations from the second observing night, that have a higher flux than that, would be from a flaring state. Also, if it indeed is a flare that is seen during the second observing night, then this flare would last the whole night without showing any decline. We also note that the Hα flux at the phase 0.192, from the second observing night, is almost identical with the flux at the phase 0.210, obtained during the first observing night (see Fig. 6). All this implies that the difference seen in the activity levels between these two nights is most likely just caused by the observations during the first observing night coinciding with the less active regions on the stellar surface.

6.2 Spot longitudes

For measuring the longitudes of the photospheric spots a spot filling factor map was obtained from the V band lightcurve using light-curve inversion methods (see e.g., Lanza

et al. (1998) for the method and Oláh et al. (2006) for the implementation used here). Light-curve inversions were decided to be used for the spot longitude determination, as tests show that the inversions result in more accurate determination of the spot longitudes than just simply determining the light-curve minimum gives (see Savanov & Strassmeier 2007). In some cases, especially when dealing with close-by spots, taking the light-curve minimum results in wrong spot longitude, whereas the inversion gives the correct longitudinal spot configuration.

For the inversion the unspotted surface temperature is set to 4000 K, which is consistent with the observations of the spectral type. Spots are assumed to be 1000 K cooler than the unspotted surface, in line with observations of other active stars. The instrumental differential V band magnitude that corresponds to the unspotted surface is estimated to be $-1\overset{\mathrm{m}}{.}25$, though as the photometric time series of EY Dra is short this parameter is relatively uncertain. However, changing the brightest magnitude will not affect the positions of the spots seen in the filling factor maps, only the filling factor values themselves. The inclination was set to 66° measured by Robb & Cardinal (1995).

One should also note that one-dimensional data, as the light-curve is, do not give information on the latitudinal distribution of the spots. This means that the spot latitude seen in the maps arises from the fact that the inversion process tends to introduce the spots to the location where they have the maximum impact on the light-curve, i.e., at the centre of the visible stellar disk. From photometry it is impossible to discern whether the light-curve minimum is caused by a single large spot or an active region consisting of several spots. For simplicity the structure causing the light-curve minimum, and seen in the spot filling factor map, is called a spot.

The resulting filling factor map of EY Dra for early July 2006 is given in Fig. 7**b**. It clearly shows two large spots on the surface. These spots are located at phases 0.4–0.6 (centred at the phase 0.53) and 0.8–1.1 (centred at the phase 0.91). This implies two active longitudes separated by 0.4 in phase. A longer time series of photometric observations is needed for confirming whether or not this configuration is the normal case for EY Dra. The earlier photometric observations (Robb & Cardinall 1995; Vida & Oláh 2006) have also shown the W shape, which implies that this kind of active longitude structure is relatively stable on EY Dra. A spot configuration where two spots are located on the stellar surface about 0.5 in phase apart is common for active stars (see e.g., Jetsu et al. 1993; Berdyugina & Tuominen 1998). Recent dynamo calculations can also produce active longitudes that are 0.25–0.5 in phase apart (e.g., Moss 2004; Elstner & Korhonen 2005).

6.3 Correlating activity in the photosphere and chromosphere

In the Sun, photospheric dark spots are often associated with bright plages in the chromosphere. Some active stars also show evidence for correlated magnetic activity in the photosphere and chromosphere. Alekseev & Kozlova (2002) investigated quasi-simultaneous photometric observations, photo-polarimetry and high-resolution spectra of a young solar-like star LQ Hya. They found evidence for a connection between plages, magnetic regions and the starspot longitudes. Similar results have been obtained also for an active binary MS Ser (Alekseev & Kozlova 2003).

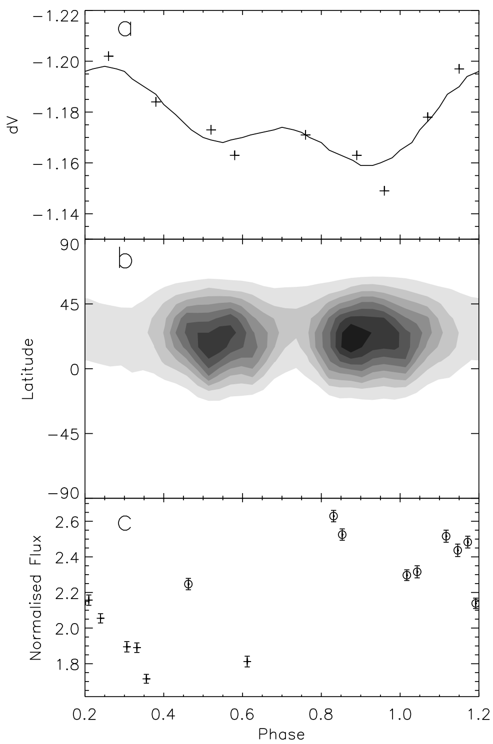

Fig. 7 Correlating photospheric and chromospheric activity. a) The differential V band observations (crosses) with the fit (solid line) obtained from the inversion. b) The spot filling factor map, where the darker colour means larger spot filling factor. c) Variation in the Hα flux (symbols as in Fig. 6). In all the plots the phases from 0.2 to 1.2 are plotted to show the active regions better.

The possible correlation between the photospheric spots and chromospheric plages on EY Dra was studied using the data presented in this paper. The spot positions determined from the light-curve inversions of the V band data (Fig. 7**a,b**) show that the photospheric active regions occur at two active longitudes: one centred around the phase 0.53 and the other one centred around the phase 0.91. On the other hand the enhanced Hα emission occurs at the phases 0.8–1.1 and another small increase is seen around the phase 0.5 (see Fig. 7**c**). Unfortunately the extent of this weaker feature cannot be determined, as there is only one observation around this enhancement. In general, the increases in the Hα emission occur near the same phases where the photospheric spots are centred. Thus, the observations of EY Dra obtained at NOT in early July 2006 can be inter-

preted as bright plages in the chromosphere associated with the photospheric active region centred at the phase 0.91, and possibly also on the photospheric active region centred at the phase 0.53.

6.4 Chromospheric pressure

The Paschen β line is expected to vary with chromospheric pressure; changing with increasing pressure from a weak absorption line to a stronger absorption line and finally to an emission line (Short & Doyle 1998). The pressure at the top of the chromosphere, or equivalently at the bottom of the transition region, is measured as a column density and given by $\log \mathrm{m}_{TR}$. According to the models by Short & Doyle (1998) the line responds to the increasing chromospheric pressure in the same way as the Hα. For low chromospheric pressure it is weakly in absorption with minimal equivalent width W_λ. As the chromospheric pressure increases the line becomes more strongly absorbent, with maximal W_λ occurring at $\log \mathrm{m}_{TR} = -4.2$. Then, as the chromospheric pressure increases further the line makes a rapid transition to emission. With $\log \mathrm{m}_{TR} = -4.0$ the line is either balanced between absorption and emission or is weakly in emission, depending on the exact model. The more precise behaviour can be seen in Sort & Doyle (1998, Fig. 3)

Our NIR spectra of EY Dra do not show any indication of an emission line around the wavelength of Paschen β. According to the models of Short & Doyle (1998) the chromospheric pressure of EY Dra is hence $\log \mathrm{m}_{TR} \leq -4$. The non-detection of the Paschen β line in the EY Dra spectra can be due to the low resolution of the observations, though a strong emission line would be visible even with this relatively low quality data.

Short & Doyle (1998) also present models for the Hα line. According to their calculations the pressure value of $\log \mathrm{m}_{TR} = -4.0$ causes the Hα to be strongly in emission, even though the Paschen β line is not yet in emission. The Hα emission observed in EY Dra supports the idea that the chromospheric pressure of EY Dra is close to $\log \mathrm{m}_{TR} = -4.0$, as with much lower pressures the Hα line would not be in emission either.

7 Conclusions

Based on the photometric and spectroscopic observations of EY Dra the following conclusions can be drawn:

- The light-curve shape indicates two active regions approximately 0.4 in phase apart. Other photometric observations of EY Dra show that this could be the normal spot configuration.
- The Hα shows strong variations during the two nights of observations. Indications for plages and prominences are seen.
- The main enhancement seen in the Hα emission occurs close to the phases of the photospheric active region that is centred at the phase 0.91. This indicates bright chromospheric plages associated with the dark photospheric spots, as is often seen in the Sun.
- Chromospheric pressure is limited to $\log \mathrm{m}_{\mathrm{TR}} < -4$, based on the non-detection of Paschen β emission.

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